

Development and Validation of a Mobile, Autonomous, Broadband Passive Acoustic Monitoring System for Marine Mammals

David M. Fratantoni
Autonomous Systems Laboratory
Physical Oceanography Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

phone: (508) 289-2908 fax: (508) 457-2181 email: dfratantoni@whoi.edu

Mark F. Baumgartner
Biology Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

phone: (508) 289-2678 email: mbaumgartner@whoi.edu

Mark P. Johnson
Applied Ocean Physics and Engineering Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

phone: (508) 289-2605 email: majohnson@whoi.edu

Award Number: N00014-08-1-0294
<http://asl.whoi.edu>

LONG-TERM GOALS

Our long-range objective is to understand the oceanographic processes that influence the distribution of whales in the ocean. In support of this objective we are developing a fully-integrated autonomous acoustic observing system capable of detecting and classifying a wide range of marine mammal vocalizations (from blue whales to beaked whales; 10 Hz–100 kHz) with proven performance. This work will ultimately improve our ability to predict whale distribution and bolster efforts to mitigate human impacts on marine mammals. High-endurance oceanographic sampling platforms such as gliders and profiling floats provide a new opportunity for acquiring acoustic signals from marine animals with immediate applications in conservation and mitigation.

APPROACH

High-endurance autonomous platforms have tremendous potential for persistent monitoring of the ocean environment, including ambient noise and marine mammal vocalizations. We have previously demonstrated the utility of such platforms by simultaneously collecting passive acoustic recordings, environmental measurements, and prey observations from a fleet of ocean gliders. In contrast to these studies, which resulted in recorded audio data that were analyzed weeks after collection, many applications require almost immediate data return to facilitate at-sea decision making. To meet this

Report Documentation Page			<i>Form Approved OMB No. 0704-0188</i>	
<p>Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p>				
1. REPORT DATE 30 SEP 2011	2. REPORT TYPE	3. DATES COVERED 00-00-2011 to 00-00-2011		
4. TITLE AND SUBTITLE Development and Validation of a Mobile, Autonomous, Broadband Passive Acoustic Monitoring System for Marine Mammals			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution,Physical Oceanography Department,Woods Hole,MA,02543			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 11
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified	19a. NAME OF RESPONSIBLE PERSON	

need, the autonomous platform must be able to acquire and rapidly process acoustic data on board, detect and classify vocalizations, and telemeter a useful summary of those detections to a ship- or shore-based station.

There is a wide variety of instrumentation and software available for collecting and analyzing marine acoustic data; however, most existing tools are optimized for either low or high frequency applications. While this is acceptable for researchers focusing on particular taxa, most conservation and mitigation efforts must address the needs of a broad range of species. For example, some species of beaked whales may be especially sensitive to active sonar while certain baleen whales are at risk from ship strikes, yet there is no single instrument capable of monitoring both taxa simultaneously from a variety of autonomous platforms (gliders, floats, drifters, moorings). We have therefore developed a low-power digital monitoring instrument that is capable of long-term autonomous detection and classification of vocalizations over the frequency range encompassing most marine mammals.

Our observing system is based on a new self-contained, low-power digital acoustic monitoring device (DMON) developed at WHOI by co-PI Mark Johnson. Under support of this program we have integrated the DMON in commercially-available gliders, profiling floats, and surface drifters to create a fleet of persistent real-time acoustic monitoring platforms. In parallel, we have developed acoustic detection and classification algorithms to identify two critical classes of marine mammals: low-frequency baleen whales (e.g., right, fin, humpback whales), and high-frequency beaked whales. The performance of these detectors will be verified at several field sites with the opportunity for independent ground-truth. The work has resulted in a modular, open-source, acoustic detector capable of installation on a wide variety of autonomous platforms, together with an understanding of how to use these platforms to maximize detection performance in fleet-relevant monitoring tasks.

This project encompassed three major efforts: detector design, hardware and software implementation, and field verification.

Detector design: Successful detector design requires a knowledge not only of the properties of the signals to be detected but also of the environment and behavior of the animals that produce them. Our approach is an integrated one in which detector design is directly informed by observations from on-going field studies. This focuses attention on the real conditions in which an autonomous detector has to operate, e.g., fluctuating ambient noise and frequent interference from non-target species. We are thus creating detection methods that are robust, extensible and verifiable from the outset.

Implementation: Detector algorithms will be implemented in real-time on the DMON, a low-power self-contained acoustic signal processing device developed at WHOI. This device has been created specifically for passive acoustic detection and so has the necessary broadband, low-noise signal acquisition capabilities. The device will be integrated in profiling floats and gliders to create a persistent detection capability. As detection algorithms mature, they will be ported to the DMON for autonomous operation. It is our desire that all elements of the DMON design be made openly available to the community under a share-alike license. This ensures that new developments do not remain proprietary while still providing recognition for contributions. We believe that this open approach is the best and most efficient way to obtain community-accepted, verifiable and inter-operable methods for passive acoustic monitoring. Initially, DMONs will be fabricated at WHOI and will be an orderable item. If sufficient orders are received, production will be transitioned to a turn-key contractor in the short-term and we will seek an alliance with an oceanographic instrument producer in the long-term.

Verification: Our detectors will be verified in two ways. First, signals from known species recorded in the field will be used for bench verification of algorithms and implementations. Complete autonomous systems will then be tested in the field using DMON to simultaneously detect and record sound. This allows performance and missed detects to be evaluated after each trial. For beaked whales, field testing will take place off the island of El Hierro in the Canary Islands, a site with coastal resident populations of Blainville's beaked whale, *Mesoplodon densirostris*, and Cuvier's beaked whale, *Ziphius cavirostris*. This site is unique in supporting simultaneous visual and acoustic observations of these rare species with low-cost shore-based operations. Baleen whale validation efforts were pursued in the northeastern U.S. in the vicinity of Cape Cod.

WORK COMPLETED

DMON hardware and software

The DMON (Figure 1) is a small self-contained acoustic detector/recorder. The device monitors up to three hydrophone channels and records sound to solid-state memory either continuously or when a detection is made. The on-board processor is capable of running multiple detection and classification algorithms simultaneously. The three input channels can be configured for wide-band (blue whale to porpoise) monitoring or for direction finding of signals in a narrower band. Compared to a PAM implementation using off-the-shelf hardware, the DMON design offers several advantages:

- (1) power consumption is <10% of what an embedded PC requires for the same computation rate. This translates into longer deployment lifetimes on platforms such as gliders with limited hotel load.
- (2) the DMON is specifically designed for low noise sound acquisition. It produces very little electrical noise enhancing its capability to detect weak signals from distant animals.
- (3) the DMON is much smaller than an off-the-shelf solution making it straightforward to install in a variety of platforms.

Disadvantages of custom devices like the DMON are their complex and non-portable software, and lack of availability to other researchers. We are addressing these issues as follows. We have developed a software infrastructure which provides a familiar programming environment for scientific programmers. The software and hardware design will be openly available and devices will be purchasable at relatively low cost from WHOI. Our vision is that the DMON form a reference design for the rapidly expanding field of passive acoustic monitoring.

Platform modification

Profiling floats are generally expendable. However, we required an ability to recover floats following an experiment in order to access large volumes of audio recordings stored onboard. Six WRC APEX profiling floats were modified with new controllers, new Iridium communications systems, internal mounting brackets for DMON hardware, and ancillary equipment (flags, lanyards, paint) required for easy recovery at sea (Figure 2). The APEX DMON hydrophone assembly (Figure 3) attaches to the float's top end cap. Four WRC Slocum gliders were internally modified to carry a DMON card set. The Slocum DMON hydrophone assembly (Figure 3) uses a standard through-hull stem design that enables its placement on the, bottom, or sides of a glider.

DMON-Vehicle integration

We have integrated the DMON into two low-power platforms capable of persistent monitoring: the Webb Research Corporation's Slocum glider and APEX profiling float. External hydrophones for both platforms provide 10Hz–60kHz monitoring. Serial communications with the vehicle controllers allow near-real-time feedback of detections via Iridium. A drifting surface float with a cabled array of DMONs has also been developed to facilitate rapid field evaluation of detection and tracking algorithms. The three platforms provide the capability to work over a wide range of spatial and temporal scales. APEX and Slocum firmware were specially modified to address the DMON hardware. Both platforms are now capable of including DMON detector output in their satellite-telemetered data streams.

Detector/classifier development

We continue to develop detection and classification software for baleen whale calls and beaked whale clicks taking advantage of extensive sound data holdings at WHOI. The baleen whale detector involves pitch tracking followed by attribute extraction and classification by quadratic discriminant function analysis (e.g. Baumgartner and Mussoline, 2010). The beaked whale detector incorporates discrimination of dolphin clicks based on spectral and click-rate cues. We are currently porting both detectors for real-time operation on the DMON and are evaluating the detection range of the beaked whale detector using sound recordings made by DMONs of whales tagged with the WHOI DTAG acoustic recording tag (Johnson and Tyack, 2003).

Significant Field Trials

Baleen Whale Studies

Great South Channel, May 2009: 2 DMONs as LF recorders in profiling floats.

Central Gulf of Maine, Nov 2009: 3 DMONs as LF recorders in glider, profiling floats

US Virgin Islands, March 2010: 2 DMONs as LF+MF recorders in profiling floats.

Great South Channel, May 2010: 3 DMONs as LF+MF recorders in gliders.

SCORE Range, Nov 2010: 3 DMONs as LF+MF recorders/detectors in glider, floats.

Great South Channel, May 2011: 3 DMONs with LF autodetect in glider, floats.

Beaked Whale Studies

Canary Islands, Nov. 2009: 4 DMONs as LF+MF recorders and beaked whale detectors

Canary Islands, May 2010: 4 DMONs as LF+MF recorders and beaked whale detectors

North Carolina, June 2010: 2 DMONs as LF+MF recorders in drifting buoys.

Azores, July 2010: 10 DMONs in MF spatial (vertical and horizontal) drifting arrays.

Almeria, Spain, August 2010: 4 DMONs as MF recorders in drifting buoys

Canary Islands, Sept. 2010: 4 DMONs as LF+MF recorders and beaked whale detectors.

RESULTS

We have used the new DMON-equipped gliders and profilers in several field trials with great success. It is premature to report substantial scientific results from these trials. However, we have been able to evaluate the performance of the DMON in record-only mode. The system is low-noise, power- and data-efficient, and reliable. We are continuing (under a related program) to develop and refine detectors, implement them on the DMON, and validate LF and MF detection capabilities using the DMON-equipped platforms.

In January 2011 we deployed one Slocum glider and two APEX profiling floats from the *R/V Robert Gordon Sprout* west of San Clemente Island, CA. All platforms (Figure 4) were equipped with DMONs configured for detection of MF beaked whale clicks. The profilers and glider worked extremely well and telemetered numerous real-time beaked whale detections. An additional DMON was deployed on the Z-Ray flying wing glider – data from this instrument was recovered after each vehicle deployment.

The APEX profilers each completed 5 12-hour dives to 800 m covering about 25 km in the center of a target region identified by Dave Moretti. The glider completed 99 dives to 200 m and covered 53 km in the same general region. To facilitate vehicle-vehicle comparisons the Slocum spent about 2/3 of its mission in the vicinity of two UW Seagliders, and the remaining 1/3 of the time near the profilers (including Haru Matsumoto's Quephone float). Post-experiment, Mark Johnson reviewed a subset of these detections and was able to confirm that the real-time beaked whale detection provided a robust first-cut of possible detections and was efficient at rejecting interfering transient sources (see Figures 5 and 6). The deep-diving profiling floats were more successful than the shallow glider and were shown to be viable platforms for persistent detection of beaked whales.

IMPACT/APPLICATIONS

National Security: Concern about potential impacts on acoustically-sensitive cetaceans has constrained some Navy training exercises and has led to lengthy court proceedings. The development of reliable methods to predict and verify the presence of cetaceans will provide the Navy with new tools to help balance preparedness with environmental stewardship.

Economic Development: Economic development brings increasing noise to the ocean from ship traffic and oil exploration. An improved understanding of the abundance and habitat of marine mammals and their use of sound will help to make economic growth sustainable.

Quality of Life: The techniques developed here will lead to improved information about the location and abundance of marine mammals. These results will facilitate improved regional management with implications on ecosystem health.

Science Education and Communication: To the extent possible, we have adopted an open-source approach whereby all aspects of the technology will be available to other researchers. Our goal in doing this is to foster community development of the device and to facilitate the availability of extensible systems for marine mammal acoustics research and training.

RELATED PROJECTS

Further refinement of DMON and relevant detectors and broad dissemination of these tools is the topic of “Beta testing of persistent passive acoustic monitors” (N000141010381; PI’s Johnson, Fratantoni, Baumgartner). The primary goal of this closely-related program is to produce 20 DMON digital acoustic monitors for distribution to a group of collaborators developing systems for acoustic monitoring of marine mammals and able to evaluate the device and its software in a range of applications. These systems will be targeted for both stand-alone use and integration in various mobile and moored platforms.

The initial development and validation of baleen whale detectors was supported under a companion ONR program “Detection and Classification of Baleen Whale Vocalizations from Autonomous Platforms,” completed in 2009. See Baumgartner and Mussoline (2010).

TRANSITIONS

The vehicle-side code required to integrate DMON with the Webb Slocum glider is now contained within the standard WRC glider software package and is publically available. Any user of a Slocum glider has immediate access to this code. Comparable code for the APEX profiler is also available.

PUBLICATIONS

Arias, A., M. Johnson, N. Aguilar, P. Madsen, and B. Mohl, 2008. “Acoustic detection of beaked whales from autonomous recording buoys,” Conference of the American and European Acoustic Societies. Paris, July, 2008.

Arranz, P., N. Aguilar Soto, and M. Johnson, 2008. “Coastal habitat use by Cuvier’s and Blainville’s beaked whales off El Hierro, Canary Islands,” European Research on Cetaceans 22nd. Holland, April, 2008.

Baumgartner, M. F., and S. E. Mussoline, 2010. A generalized baleen whale call detection and classification system. *J. Ac. Soc. Am.*, submitted.

Beedholm K., P. Madsen, and M. Johnson, 2009. “Discriminating beaked whale clicks: there is little reduction in detection performance by the introduction of an effective discrimination step,” 5th Animal Sonar Symposium. Kyoto, Sept. 2009.

Boisseau, O., C. Lacey, T. Lewis, T. Thorne, A. Moscrop, D. Gillespie, D., and N. Aguilar Soto. “Mid-Atlantic surveys for beaked whales: the potential for acoustic prediction of critical habitats” 23rd Conference of the European Cetacean Society. Istanbul, Turkey.

DiMarzio, N., D. Moretti, J. Ward, R. Morrissey, S. Jarvis, E. McCarthy, M. Johnson, P. Tyack, D. Claridge, C. Dunn, T. Marques, and L. Thomas, 2009. “Passive acoustic density estimation of Blainville’s beaked whales (*Mesoplodon densirostris*) using group localization combined with click counting,” 4th International Workshop on Detection, Classification and Localization of Marine Mammals using Passive Acoustics. Pavia, Sept. 2009.

Gordon, J., D. Gillespie, M. Caillat, D. Claridge, D. Moretti, J. Dalgaard Balle, O. Boisseau, N. Aguilar de Soto, S. Viallelle, and I. Boyd, 2009. "Detection and classification of beaked whales using towed hydrophones and real-time software for discrimination and localization," 23rd Conference of the European Cetacean Society. Istanbul, Turkey.

Johnson, M. "Quantifying the performance of passive acoustic detectors for beaked whales. Workshop "Beaked whales and active sonar: transiting from research to mitigation," held at the 23rd Conference of the European Cetacean Society. Istanbul, Turkey.

Johnson M., and N. Aguilar de Soto, 2009. "Performance evaluation of passive acoustic detectors for beaked whales," Proc. of the workshop on beaked whales and sonar, European Cetacean Society.

Johnson M., L. S. Hickmott, N. Aguilar Soto, and P. T. Madsen, 2008. Echolocation behaviour adapted to prey in foraging Blainville's beaked whale (*Mesoplodon densirostris*). *Proc. R. Soc. B*, **275**, 133-139.

Johnson M., T. Hurst, A. Arias, and N. Aguilar de Soto, 2009. "Validating acoustic monitors for marine animals: field experience with beaked whales and Digital Acoustic Monitors," Meeting of the Ac. Soc. Am., Portland, May 2009.

Johnson, M. P., and P. L. Tyack, P. L., 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. *Oceanic Engineering, IEEE Journal of*, **28**(1), 3-12, doi: 10.1109/JOE.2002.808212.

Parks S. E., C. W. Clark, M. Johnson, and P. L. Tyack, 2009. "Simultaneous acoustic tag and bottom mounted acoustic recorder detection of right whale calls in the Bay of Fundy," Meeting of the Ac. Soc. Am., Portland, May 2009.

Ward J., N. DiMarzio, S. Jarvis, D. Moretti, R. Morrissey, M. Johnson, and P. Tyack, 2009. "Mesoplodon densirostris transmission beam pattern estimated from passive acoustic bottom mounted hydrophones and DTAG recordings on multiple whales," 4th International Workshop on Detection, Classification and Localization of Marine Mammals using Passive Acoustics. Pavia, Sept. 2009.

Ward, J., R. P. Morrissey, D. J. Moretti, N. DiMarzio, S. Jarvis, M. Johnson, M., P. L. Tyack, and C. White, 2008. "Passive acoustic detection and localization of *Mesoplodon densirostris* (Blainville's beaked whale) vocalizations using distributed bottom-mounted hydrophones in conjunction with a digital tag (DTAG) recording." *Can. Acoust.*, **36**, 60-73.

Zimmer, W. M. X., J. Harwood, P. L. Tyack, M. Johnson, and P. T. Madsen, 2008. Passive acoustic detection of deep diving beaked whales. *J. Ac. Soc. Am.*

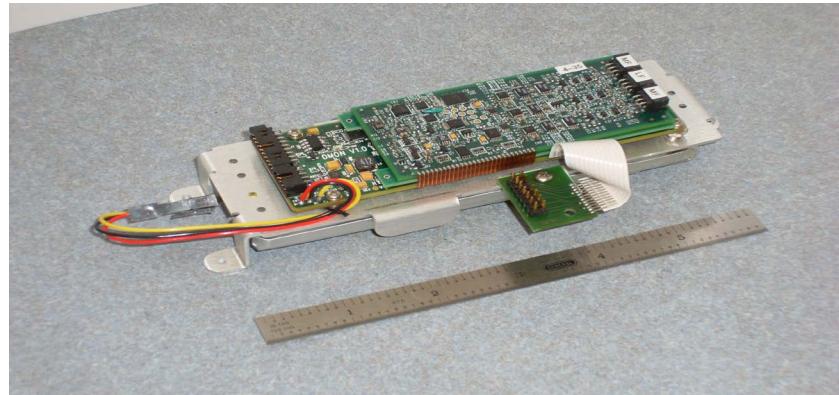


Figure 1: DMON board set in glider-ready format

The DMON is a set of two circuit boards capable of wide bandwidth acoustic recording and real-time detection. The device consumes little power making it ideal for low hotel load autonomous vehicles like gliders.



Figure 2: Photo of APEX Profilers with installed DMON and 3-channel hydrophone assembly (top end cap to left of flag). Profilers were modified to enable post-experiment recovery, including addition of Iridium 2-way satellite communications.

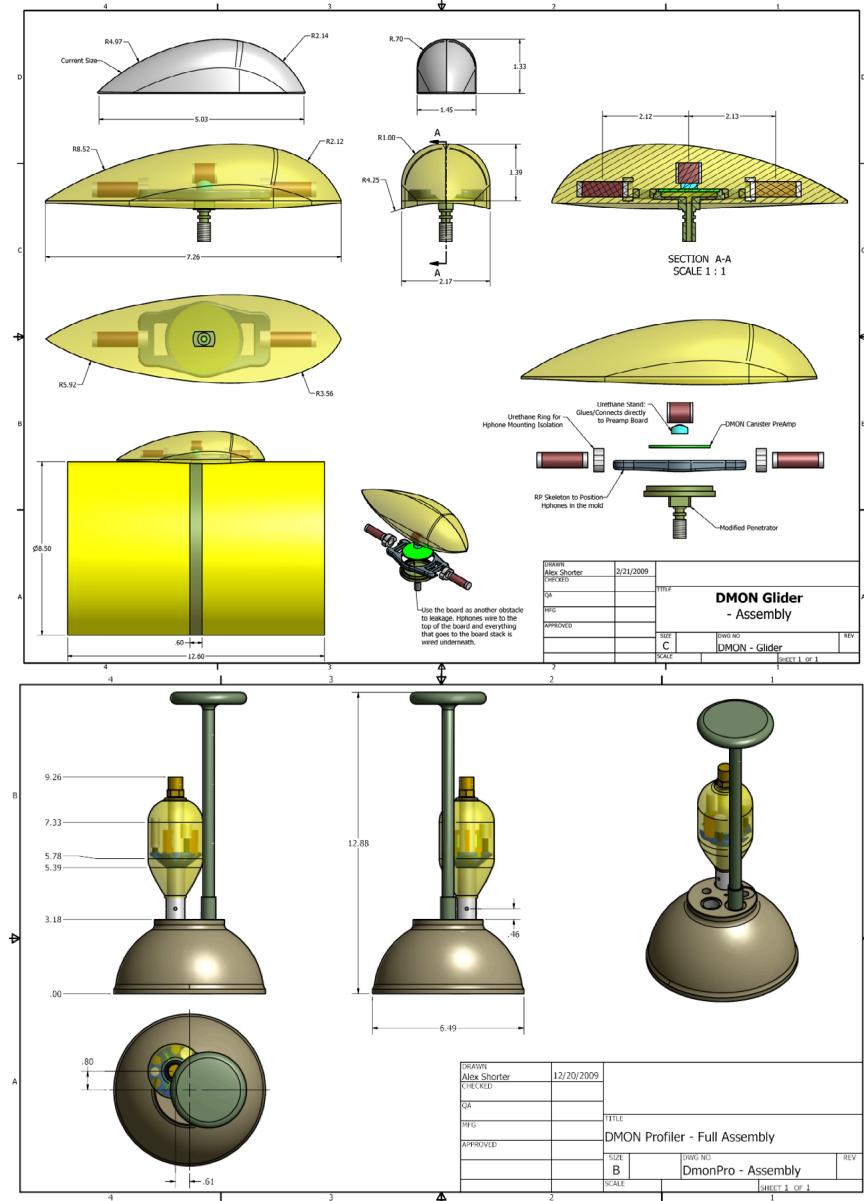


Figure 3: External multi-channel hydrophone assemblies developed for (top) Slocum glider and (bottom) APEX Profiler.

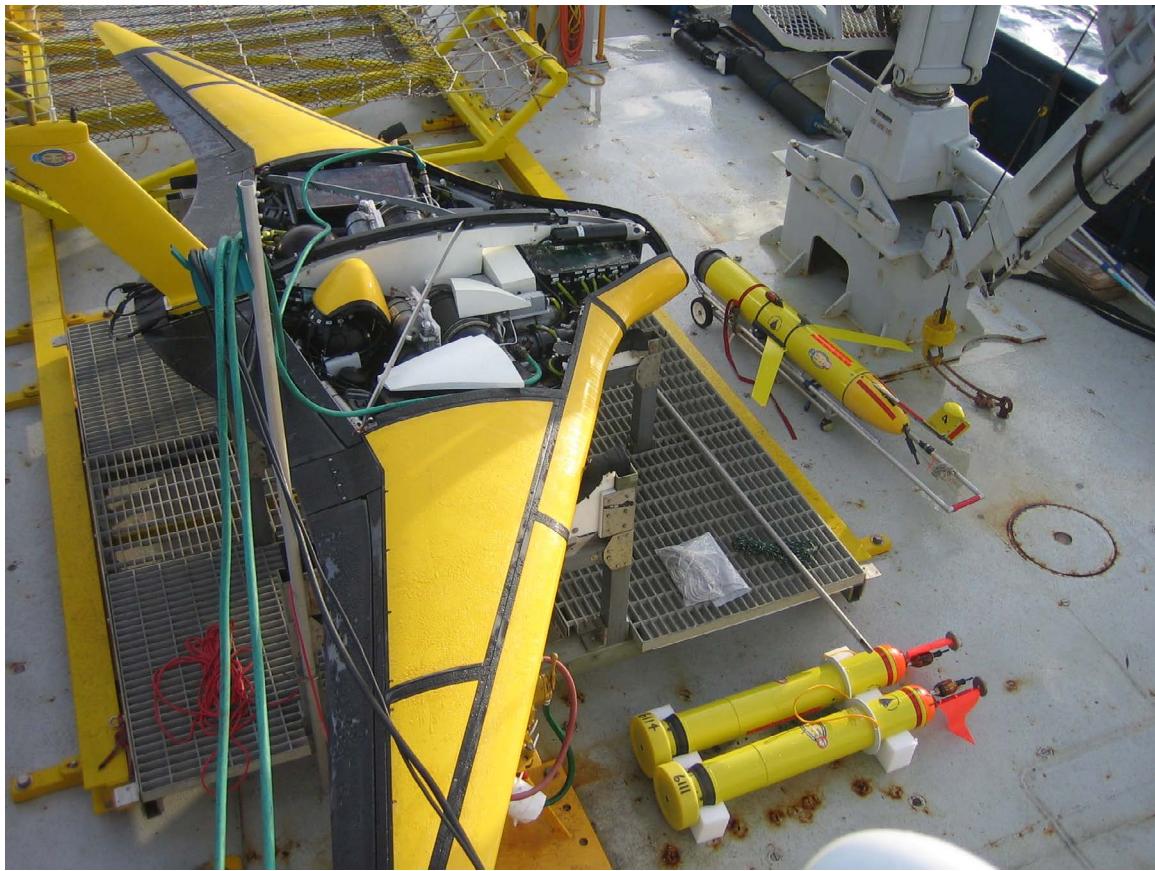


Figure 4: Four platforms equipped with DMONs and deployed in January 2011 in southern California. The Z-Ray Glider (Gerald D'Spain) carried an internally-recording DMON, while the two APEX profiling floats and the Slocum glider each carried customized, fully-integrated DMON systems.

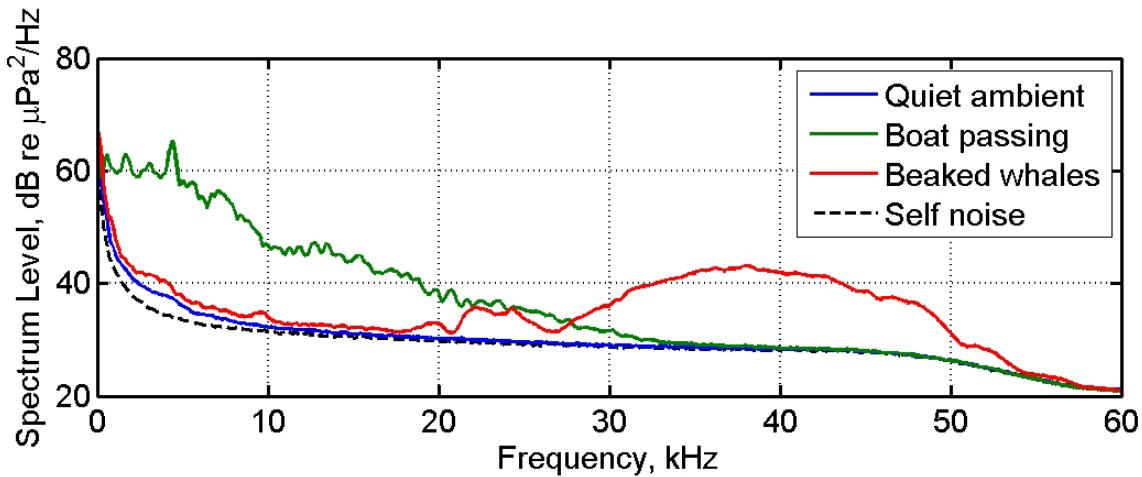


Figure 5: Ambient noise as recorded by a DMON-equipped profiler in a coastal environment in southern California.

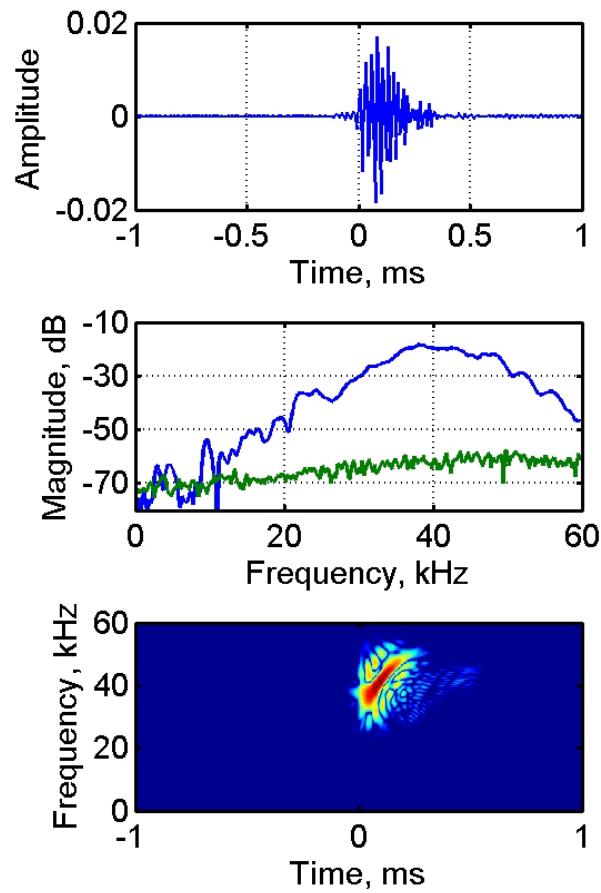


Figure 6: Example of a Cuvier's beaked whale click recorded and autonomously detected by a DMON-equipped APEX profiler in a coastal environment in southern California.